IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 12, Issue 3 Ver. V (May – June 2017), PP 37-45
www.iosrjournals.org

Design and Implementation of Power Distribution Module of Low Earth Orbit Small Satellite

A.Elmayah[1], A. Prof. Dr. R. Moustafa[2], Dr. Fawzy Eltohamy[3]

Abstract*: Power distribution system is a vital system and considered as one of the most important subsystem of the whole satellite. This paper basically discusses the design of the power distribution module (PDM) of a low earth orbit small satellite. The designed PDM draws24 Volt unregulated power from the Power Control Distribution Unit battery charge regulator module (PCDU-BCR)and then provides regulated 3.3 Volt, 5 Volt, 12 Volt and unregulated 24 Volt to the satellite subsystems. The PDM implements current sensing, current limiting, switching and protection of the loads.Moreover the PDM design fulfils internal redundancy to achieve the required reliability.The switching algorithms are built to control the loads' operation during the satellite different modes of operation through the PDM design configuration.The design of the PDM is based on the Commercial Off the shelf Components (COTS) that is cost efficacious. Therefore this paper is valuable in building of the small satellites' Electrical Power Systems (EPS) that are low cost but highly efficient. The satellite mission input requirements for EPS are verified by the output results of the implemented PDM.*
Keywords*: Power distribution module- DC-DC converter- Current sensor- Limiting switches- Commercial Off the shelf Components (COTS)*

I. Introduction

Small satellites with a mass between 10 to 500 kg have become a competitor to large satellites with a mass of over 1000 kg. This development has come about through the technological advances in micro-electronics. Small satellites are obviously less cost especially for launch, Microsatellites considered as a category of small satellites of mass up to 100 Kg and dimensionsalmost 50x50x50 cm^3, that are used mainly as satellite communications, space science, remote sensing and in-orbit technology demonstration as well as providing a unique facility for hands-on training of young science and engineer students, Microsatellites composed mainly of two major compartments the payload and the platform compartments which are divided to a certain number of subsystems as shown in fig. (1) **(1)**

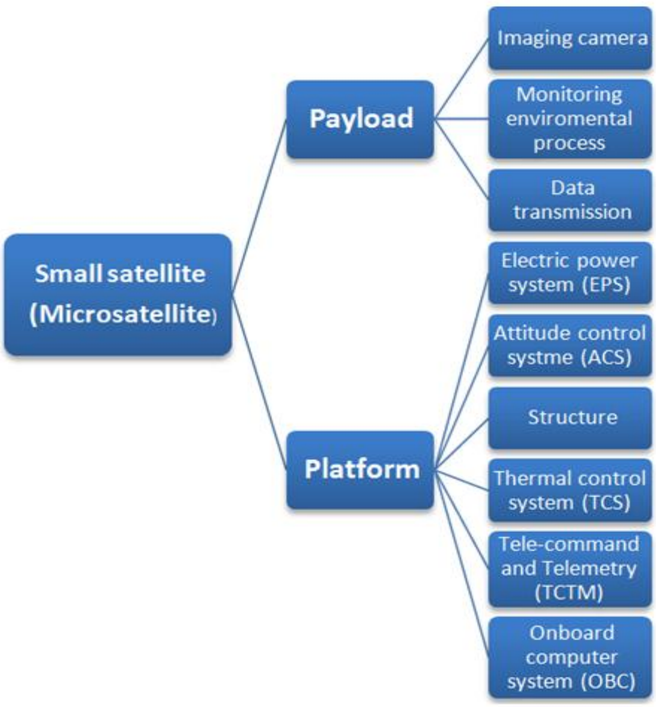


Figure 1 Microsatellite architecture

II. Electrical power system

Electrical Power system of the satellite can be characterized as the backbone because all of the functions are reliant upon it. EPS provides, stores, distributes, and controls satellite electrical power, EPS of satellite consists of two sources; the primary source is the solar energy. The secondary energy source is the battery which stores excess energy coming from the solar panel. This energy is utilized during eclipse, when there is no sunlight.This power is then basically regulated and distributed to the subsystems according to their requirements.(2) EPS main tasks can be realized by four elements as shown in fig. (2). this research paper focuses on the power distribution module of the satellite.

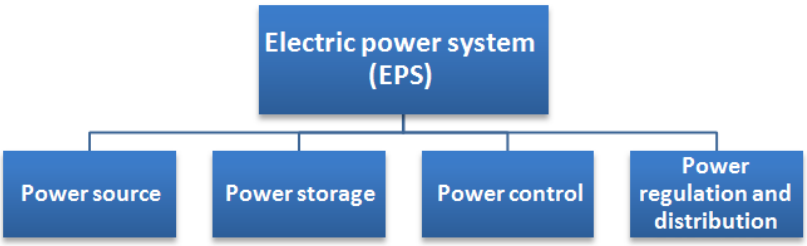


Figure 2 EPS major functions

III. PDM mission requirements

PDM major requirements is to regulate and distribute electrical power to the satellite loads, it shall obtain$24^{+1.3}_{-1.6}$ Volt from the primary power source depending on the charging value of the battery, this module shall supply this unregulated voltage to few loads moreover it shall convert these input voltage into 3.3V, 5V and 12 V regulated voltages and then distributes them according to the loads electrical requirementsmentioned in table (1).(3)

The PDM must be also capable to execute the following roles

- Power conversion and regulation.
- Control switching of the loads that are switchable
- Current sensing
- Protection against overcurrent
- Receive control commands from on-board computer according to the planned satellite mode of operation
- Fulfils the system required reliability

No.	Load	Voltage [Volt]	Nominal Current [Ampere]	Switching type
1	Reaction wheel assemblies (FOG)	5	0.15	Switchable
2	Wheel drive electronics (WDE)	5	0.1	Switchable
3	Attitude control computer (ACC)	5	0.2	Switchable
4	Fine sun sensor (FSS)	5	0.1	Switchable
5	Star tracker (ST)	5	0.2	Switchable
6	Onboard computer (OBC)	5	0.15	Auto reset
7	Payload , Power and data handling (PPDH)	24	0.4	Switchable
8	Magnetometer	24	0.1	Switchable
9	ACC magnetometer (ACC-Mag.)	24	0.1	Switchable
10	Reaction wheel (RW)	24	0	Switchable
11	Space borne GPS receiver	12	0.17	Switchable
12	Telemetry and Tele-commands (TCTM)	24	0.1	Auto reset
13	PCU digital	3.3	0.2	Auto reset

Table 1 Loads electrical requirements

IV. PDM architecture

Power regulation is a vitalpart of PDM.There are two main methods used for this. Either we use centralizedpower regulation system or decentralized power regulation system.Both have their own pluses and drawbacks which are listed in table (2). According to our requirements we have used centralized power regulation system since it is more economic and also less space is required. The main disadvantage of decentralized system is the amount of time and space required to build it. Also distributed systems are not very economic for small satellites.(4)

Table 2 Comparison between Centralized and Decentralized PDM power regulation

No.	Factor	Centralized System	Decentralized System
1	**Cost**	Less cost as smaller number of components	More cost as greater number of components
2	**Mass**	Small	large
3	**Complexity**	Low for microsatellites	High for microsatellites
4	**No. of DC-DC Converters**	Less	More
5	**Utility of that architecture**	Hardly do adapt to changes in requirements from mission to mission	Greater over a wider range of mission requirements
6	**Optimization**	Less optimum as load variation at the point of load is usually smaller than at the system level	More optimum as a converter is selected for a specified subsystem

V. PDM external interfaces

Power Control and Distribution Unit (PCDU) consists of three modules as shown in fig. (3).

– Power Control and Distribution Unit battery charge regulator module (PCDU-BCR)
– PDM
– Power Control and Distribution Unit digital module (PCDU-Dig)

PDM has external interfaces with PCDU-BCR receiving unregulated voltage ranges from 25.3V when the storage battery is fully charged to 22.4V when the battery is discharged to the designed level of depth of discharge (DOD), in addition interface with PCDU-Dig which sends commands and receives telemetry, PCDU-Dig controls the operation of the satellite subsystems according to the modes of operation through commands switching ON/OFF also it controls the operation of the buck converters responsible for the supplying the required voltages values to the loads, also it is used in the OFF nominal situations to switch OFF a load according to the overcurrent values read by current sensor and to switch between the nominal DC converter to the redundant converter in case of abnormal operation.

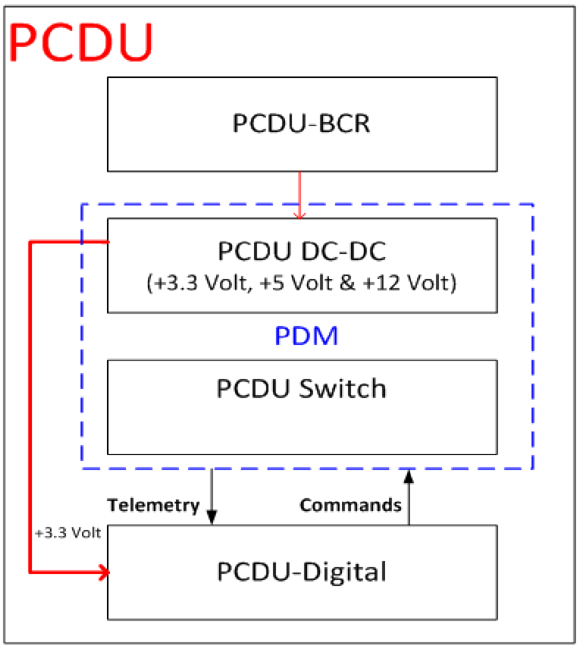


Figure 3 PCDU internal modules

VI. Design of PDM

PDM consists of six DC-DC buck converter of type LM2596 of three step down values 3.3V,5V and 12V , each pair is connected in parallel to realise the redundancy concept and each converter can be switched ON/OFF by a control command from the PCDU-Dig according to a certain algorithm, also it consists of five switches of type MAX890L to control switching of 5V subsystem loads and five switches of type SIP32419 to control switching of unregulated voltage 24V subsystem loads and to control switching of 12V subsystem load and three switches of type SIP32429 to control switching of unregulated voltage 24V for essential subsystem loads, in addition to eighteen current sensor of type ACS712ELCTR-05B to read the current value of the 5V DC-DC buck converter and the subsystems loads, PDM receives commands from PCDU-Dig to control operation of the loads switches and sends telemetry concerning current values and fault signals from the switches.as shown in fig (4).

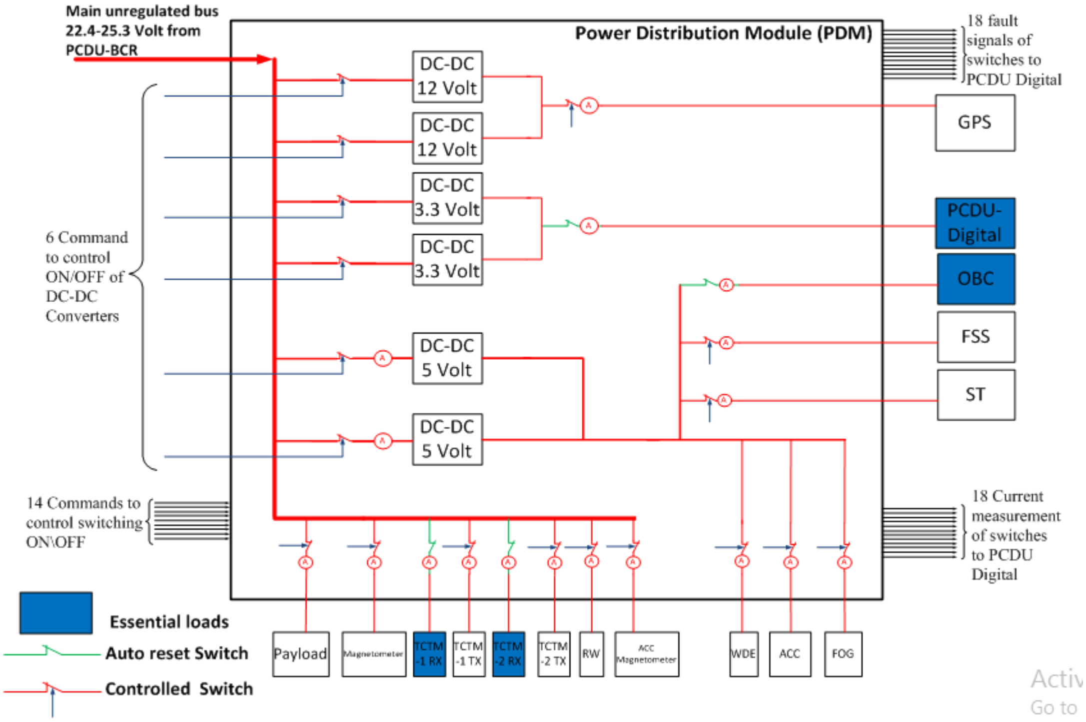


Figure 4 PDM internal and external interfaces

VII. DC-DC Converter

The LM2596 converter is a highly efficient step down switching regulator of wide input range up to 40V with a switching frequency of 150 kHzand operating temperaturefrom -40 to 125 °C; it is capable of driving a 3-A load with excellent line and load regulation, it is featured by Low Power Standby Mode typically 80 µA, thermal shutdown and current limit protection.LM2596 buck converter is designed to supply three values of regulated voltage as required to the loads; Converter circuit is designed as shown in fig.(5),the efficiency of LM2596 increases as the value of the output voltage increases at typical input voltage about 24V as shown in fig.(6) and its value for each step down voltage is mentioned in table (3), the selection of the inductor value depends the maximum input voltage and the maximum total load current for each converter as shown in fig. (7), all the buck converters circuits' components designed parameters are stated in table (3).(5)

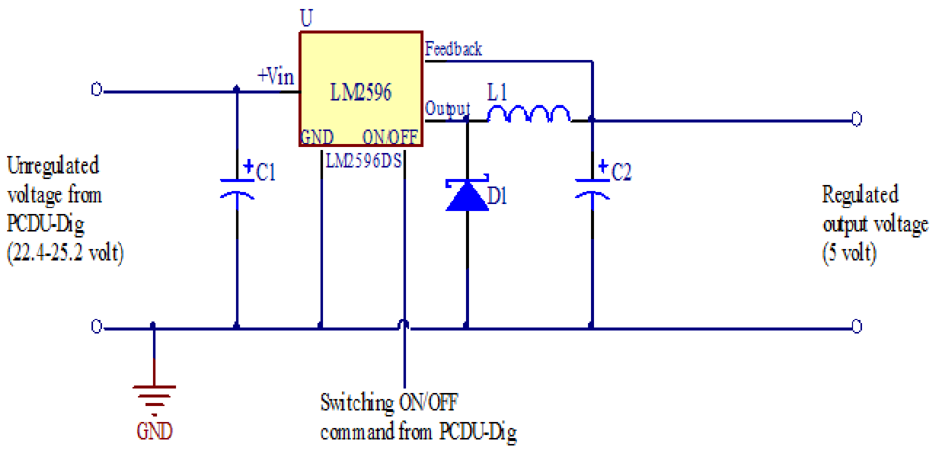


Figure 5 LM2596 DC-DC converter circuit

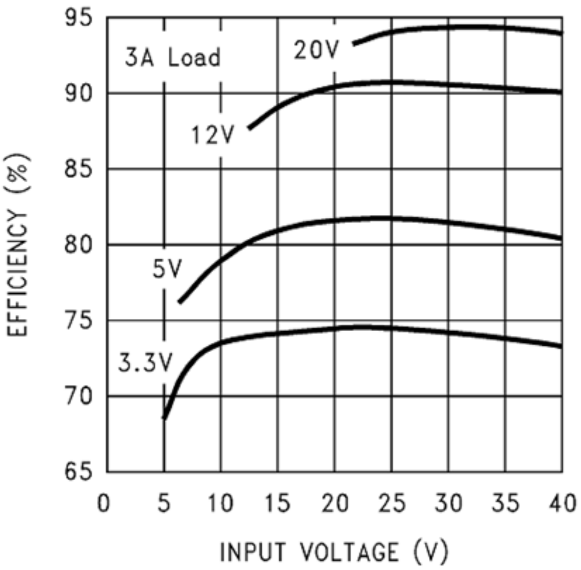
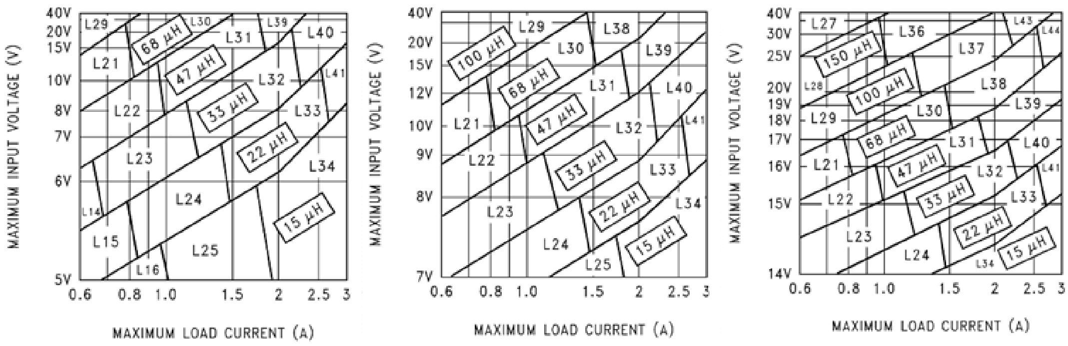


Figure 6 DC-DC converters efficiency

No.	Design parameters	3.3 Volt DC-DC buck converter	5 Volt DC-DC buck converter	12 Volt DC-DC buck converter
1	**Output voltage (V)**	3.3	5	12
2	**Efficiency (%) at input voltage 22.4-25.2 Volt**	74	81	90
3	**Maximum output current (A)**	0.7	2.05	0.17
4	**Input capacitor C1**	470µF/50V	470µF/50V	470µF/50V
5	**Output capacitor C2**	330µF/10V	330µF/10V	68µF/25V
6	**Inductor L1**	68µH	68µH	150µH
7	**Catch diode D1**	Schottky diode 3A-30V	Schottky diode 3A-30V	Schottky diode 3A-30V

Table3 DC-DC converters design parameters



Buck converter 3.3V Buck converter 5V Buck converter 12V

Figure 7 Inductor selection graphs

VIII. Current limiting switches

PDM major functions areswitching of the loads according to the satellite modes of operation and protection against overcurrent which can be achieved by using command controlled current limiting switches and according to the subsystems electrical requirements we use three types of limiting switchescomprises of five switches type MAX890L, five switches of type SiP32419 and three switch of type SiP32429.

The firstswitch MAX890L is a smart P-channel MOSFET power switch which characterized by operating at low voltage level ranging from + 2.7V to 5.5Vwith maximum current limit 1.2A which is ideal with loads operating at 3.3V and 5V, its main features are that it has low quiescent current, operating temperature range from -40°C to 85°C, thermal shutdown, programmable current limit and fault indicator output, it is controlled by command of $\overline{ON}$input low voltage maximum 0.8V and $\overline{ON}$ input highvoltage minimum 2V.

In the situation of an output short circuit or current-overload condition, the current through the switch is limited by the internal current-limiting error amplifier up to 1.5 x I_{LIMIT}, In case of a higher current than

$1.5xI_{LIMIT}$during an output short-circuit condition, the switch turns off and disconnects the input supply from the output providing a fault output signal$(\overline{FAULT})$ goes low when the current exceeds limit of $1.5xI_{LIMIT}$ or when the die temperature exceeds +135°C.(6)

The design of the MAX890L circuitis composed of an input capacitor C1of value 1µF to limit the input voltage drop during momentary output short-circuit conditions and output capacitor C2 of value 0.1µF to prevent inductive parasitics during turn-offand the current limit can be programmed by a resistor R1 connected to the ground as shown in fig. (8) And it is calculated by the following equation.

$$R_{SET} = \frac{1.38 * 10^3}{I_{LIMIT}}$$

Where $I_{LIMIT}$is the designed current limit value

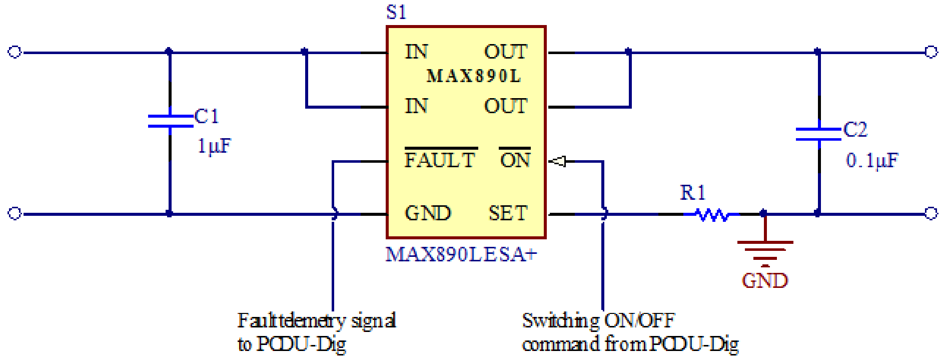


Figure 8 MAX890L Current limit switch circuit

The second switch SiP32419 is a current limit load switch which characterized by operating at wide maximum ratings of input voltage level ranging from -3V to 30V with maximum current limit 3.5A which is ideal with loads operating at unregulated voltage 24V, its main features are that it has low quiescent current, operating temperature range from -40°C to 85°C, thermal shutdown, programmable current limit and fault indicator output, it is controlled by command of ONinput highvoltageminimum 1.5V and OFF input lowvoltagemaximum 0.6V.

In the event of an output short circuit or current-overload condition, the current through the switchwill be limited to the programmed set point and in case that the over current event exceeds 7ms, the switch is turned OFF and the FLG pin is pulled low, Also the SiP32419 has an over temperature protection circuit (OTP) which will shut the switch off if the junction temperature exceeds about 135 °C. The OTP circuit will release the switch when the temperature has decreased by about 40 °C.

The design of the SiP32419 circuit composed of an input capacitor C1 of value 2.2µF to minimize transients on the inputand output capacitor C2 of value 0.1µF to accommodate load transient and R1 of value 100KΩ in which the signal is pulled by it, the current limit can be programmed by a resistor R2 connected to the ground and it is calculated by the following equation as shown in fig. (9).(7)

$$R_{SET} = \frac{1.24}{I_{LIM}} * 5000$$

Where $I_{LIM}$is the designed current limit value

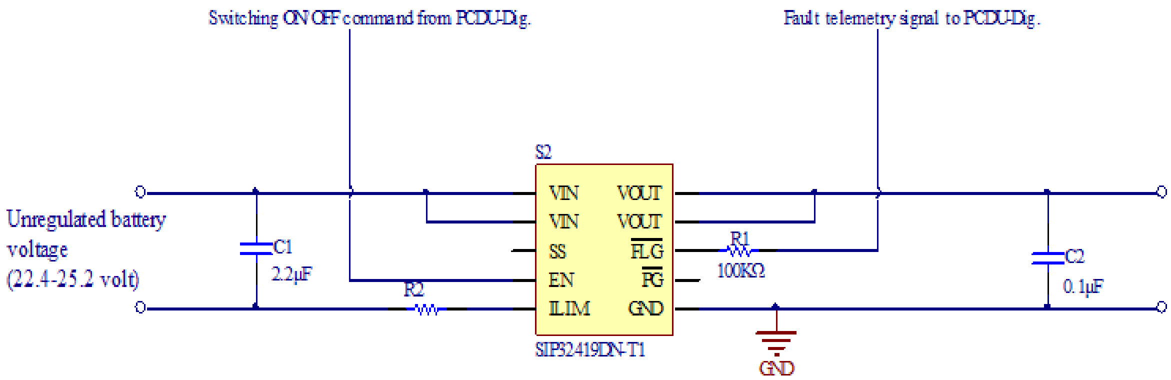


Figure 9 SIP32419 Current limit switch circuit

The third switchSiP32429which is used for the essential loads has the same characteristics as SiP32429 but it is specified that it will turn OFF the switch under fault conditions, and re-try to switch itON through the full soft start procedure 150 ms after the switch is OFF if there is no over temperature fault. The detailed timing diagram of the SiP32429 showing switch operation during the fault conditions both overcurrent and over temperature as shown in fig. (10).

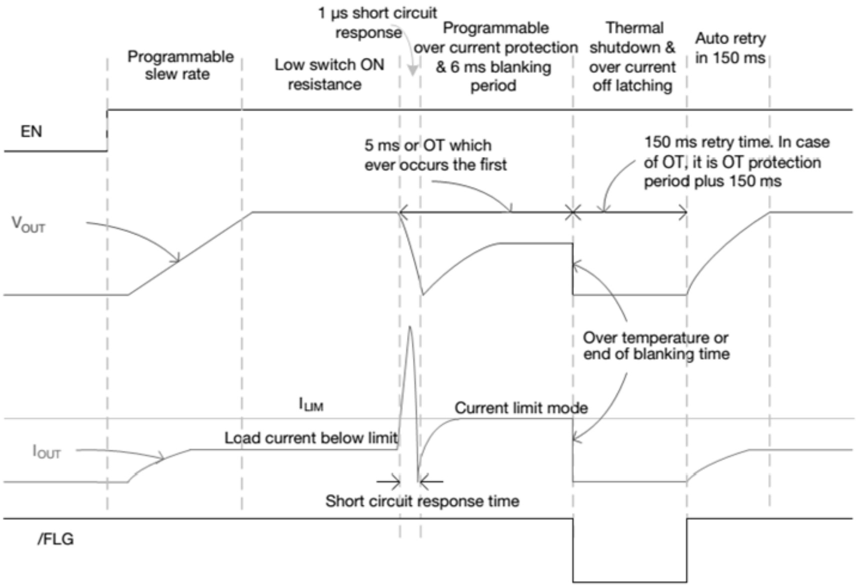


Figure10 SiP32429 current limiting switch timing diagram

Current sensor element

ACS712ELCTR-05B-T is a hall effect-based linear current sensorwith 2.1 kV_{RMS}voltage isolation and a low-resistance current conductor which characterized by 185 mV/A output sensitivity, operating temperature range from -40°C to 85°C, output voltage proportional to DC currents, 5 µs output rise time in response to step input current, with total output error 1.5% at T_A= 25°C and overcurrent fault protection. The design of the ACS712 circuit composed of C1 bypass capacitor connected between V_{CC} and the ground and C2 filter capacitor which is connected between the FILTER pin and the ground and it is recommended for noise management, the design of the filter capacitor impacts on several parameters noise value (mA), rise time (µs) and power-on time (µs)and according to our system requirements we need to reduce the noise as much as we can for this reason C2 must be increased but still another constrains thatare consequently increased, rise time increase causes to decrease the number of the current reading per second and power-on time increase causes to increase the response time of the current sensor internal components to give an output as shown in fig. (11) & fig. (12). (8)

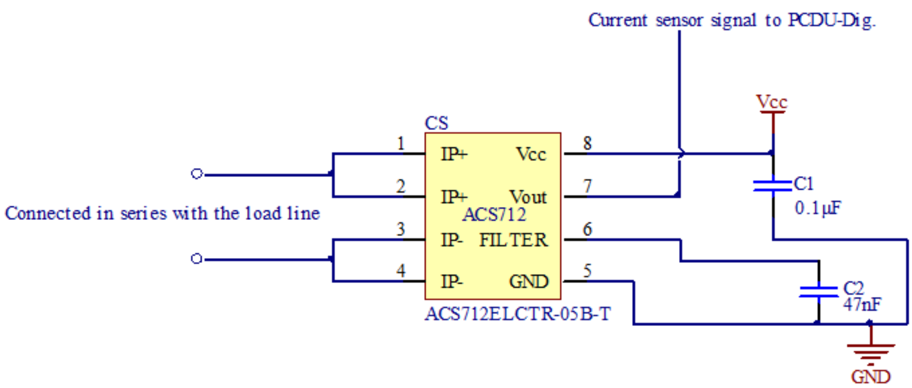


Figure11 ACS712 current sensor circuit

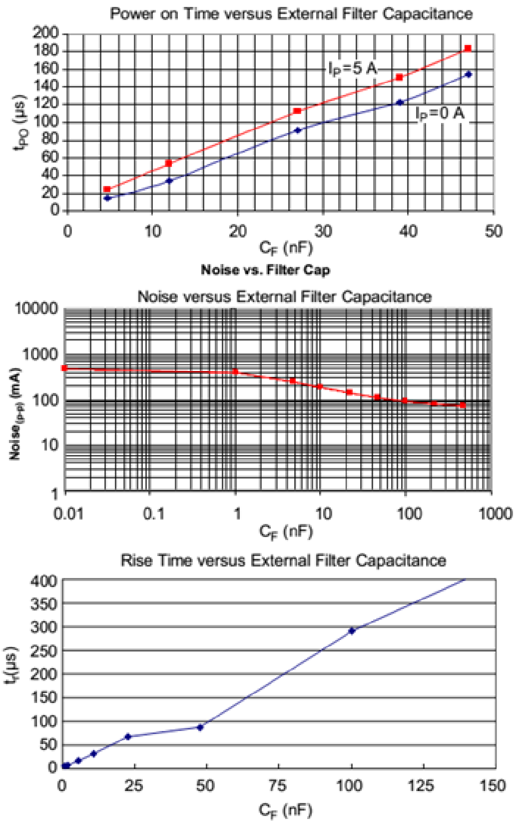


Figure 12 Filter capacitor value impact onnoise, power on time &rise time

IX. Space design attributes

A. Space radiations

These radiations can affect the performance of the components. Hence special types of components are used in designing that are safe to these radiations. These components are known as radiation hardened components. However this is supposed to be a low cost microsatellite therefore we have usedCOTS components instead. COTS are selected based on best practices, and radiation tested to limits based on the mission requirements, the PDM is implemented by using components that are previously used in similar missions as MAX890L & SiP32419, and other components must be functionally testedto ensure its ability to operate normally under these radiations.(9)

B. ReliabilityReliability which is an important parameter for space design can be improved by increasing the component redundancy but in small satellites is that lesser space is available and the components are larger due to the redundancy factor. So while selecting the components we had to consider those with high efficiency and lesser space occupied.The desire to optimize for reliability also places some guidelines on component choices. Sufficient de-rating is required to ensure components are not over-stressed, and the operating temperature range of components must be acceptable, the PDM is implemented by using redundant controlled DC-DC buck converter in each supply line so that in case of failure of one converter, this one will be switched OFF and other one on the same line with be switched ON according to the readings of the current sensor also the limiting switches de-rating are carefully selected to avoid any stresses to sustain the reliability value during the whole life time.

C. Cost and availability

This factor plays an important role in driving the design parameters. Most space missions use special space grade or radiation hardened components that drives the cost of electronics to extremes, In addition to being very expensive, space grade components are also generally harder to obtain than their commercial counterparts. Long production and qualification lead times limits the availability. The availability of components is also an important factor if functional prototypes are to be constructed within reasonable time frames, as basing the design on industrial grade components allows components to be chosen which are on stock at distributors.Choosing COTS components is definitely a tradeoff between reliability and cost/availability.

However, the low total cost of the project and the limited lifetime of the mission constitute that this tradeoff is acceptable.

D. Power efficiency

Because of the very limited available power in a microsatellite, power efficiency is one of the key concerns in design parameterstherefore we used LM2595 DC-DC buck converters which have a slightly high efficiency specially at greater input voltage, also we used switches of low quiescent current in order to minimize the dissipated power, moreover we used current sensor of low supply current in order to reduce the power consumption of PDM.

E. Thermal control

Temperature of the components needs to be checkedand controlled to maintain the temperature within their working range. Some of the components might generate too much temperature and hence they need to get rid of this temperature by the methodof thermal conduction. Also some of the components may get too cold due to the cold temperature environment of space. Hence a heater is also employed in the module which will turn ON when the temperature falls below the lower limit.Orwe may insulate them to avoid any heat loss.(10)

X. Conclusion

In this paper, the main design of the PDM of a small satellite has been reviewed. We have seen that this module is able to provide regulated voltages and currents. In addition this PDM design fulfills and ensures the mission requirements and the satellite subsystems electrical specification also in our design we maintained that our PDM must be fast, reliable and efficient; the final design will be based on the commercial on the shelf components (COTS) after passing through robust testing so that it can operate in the harsh space conditions.

References

[1] HENRY HELVAJIAN AND SIEGFRIED W. JANSON, EDITORS.SMALL SATELLITES: PAST, PRESENT, AND FUTURE. s.l. : Aerospace Press, 2008, 2008.
[2] James R. Wertz, Wiley J. Larson.Space Mission Analysis and Design. United states of America : Microcosm Press, 1991.
[3] Patel, Mukund R.Spacecraft power systems. s.l. : CRC Press, 2000.
[4] Distributed EPS in a Cubsat Application. Burt, Robert.
[5] LM2596. Instruments, Texas.
[6] MAX890L. products, Maxium integrated.
[7] SiP32419. Siliconix, Vishay.
[8] ACS712. microsystems, Allegro.
[9] Radiation effects and COTS parts in smallsats. Sinclair, Doug. AIAA/USU.
[10] Peter Fortes, John Stark , Graham Swinerd.SPACECRAFT SYSTEMS ENGINEER. s.l. : Wiley, 2004
[11] Small Student Satellite Power Distribution Module. Javed, Nizwa. 2015, Student Research Paper Conference.
[12] A.K.Hyder, R.L. Wiley.Spacecraft power electronics. s.l. : British Library, 2003.